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PREFACE

This work was undertaken for the Defense Advanced Research Projects Agency, under a task entitled "Micro-Electro-Mechanical Systems (MEMS) Development and Insertion," as a part of a program to incorporate MEMS technologies into defense systems and platforms. This document was originally presented at the AIAA Fluid Dynamics Conference in Albuquerque, New Mexico, on 15 June 1998, and is published in the conference proceedings.

MEMS IN TURBINE ENGINES

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Introduction

This document analyzes the use of micro-electromechanical systems (MEMS) in turbine engines. Potential applications of MEMS include sensor, actuator, power, and communication subsystems. In addition, there is significant analysis of technical and policy barriers to the transition of MEMS into engines. Briefing slides from a presentation on this topic delivered at an AIAA Fluid Dynamics Conference are included as an appendix.

MEMS

MEMS are micron-scale devices that integrate novel sensing and actuation functions with traditional micro-electronics-based data processing and control systems. Proponents of MEMS development list a number of advantages of systems based on these devices over traditional "macro-scale" systems, including:

Cost of Fabrication—Batch fabrication of MEMS based on processing technologies developed by the semiconductor microelectronics industry can greatly reduce systems production costs.

Size, Weight, Power Reduction—Reduction of existing system sizes without loss in functionality often reduces energy consumption, improves system efficiency, and provides access for sensors and actuators to previously inaccessible spaces.

Real-time sensing, monitoring, and control of the environment—These capabilities allow for user-controlled or automated response to anticipated problems before failure, and improve system robustness to unexpected events.

Performance advantages—Some specific applications of MEMS provide theoretical advantages over macro-scale systems, including materials performance advantages, reduction of losses for RF applications, and improved mixing characteristics in microfluidic systems. This benefit is multiplied when arrays of MEMS sensors and actuators are used in control systems.

The transition of MEMS technologies from research curiosities to practical systems and commercial products involves identification of specific, high-impact applications for MEMS, and the development of realistic strategies for development, testing, and insertion of the devices into real systems.

Most current applications of MEMS focus on the simple replacement of existing systems with MEMS-based systems to reduce size and cost. However, the real benefits of MEMS technology will be seen through the exploitation of the advantages of these replacement systems in developing entirely new capabilities that result from microscale control over macro-scale phenomena.[1] The challenge for the MEMS developer and user communities is to identify the specific applications that best exploit these new capabilities and to develop MEMS designed for use in solving real-world engineering problems.

Engine Applications of MEMS

Turbine engines represent an important opportunity to demonstrate the innovative use of MEMS in the control of large, complex systems. Defense applications of turbine engines range from jet engines to cruise missiles to stationary power supplies for fixed installations. The military engine market is extremely large, with over 50,000 systems fielded by the Department of Defense (DoD). The Air Force has identified airbreathing propulsion as a key enabling technology for all of its future advanced system concepts.[2] Since combined engine and fuel weight is approximately 50 percent of takeoff gross weight of most military aircraft, reducing this load has become a key focus. The government-funded Integrated High Performance Turbine Engine Program (IHPTET) is an example of attempts to create more affordable, robust, and high-performance engines in the future.

Commercial markets are much larger—analysts estimate that from 1997 to 2006, the total value of the turbofan and turbojet aeroengine market alone will be $136 billion, with approximately 40,000 of these engines being produced.[3] Government initiatives, commercial market size, and competition in the turbine engine industry will all serve to help finance and promote technological innovation, making this an ideal situation for the development and insertion of MEMS.

Improvements in existing turbine engine technology could result in huge cost savings for government and industry alike. Advances in technology could

- reduce the life-cycle costs of systems through condition-based maintenance
- improve performance of military aircraft and munitions so that fewer platforms are required to perform assigned missions
- reduce instrumentation requirements on test rigs
- reduce time-to-market of new systems by reducing the cost and improving the quality of engine tests

A number of industry and government organizations have begun to explore the possibility of using MEMS sensors and actuators in turbine engine systems. Drawn from their studies, the following list of specific MEMS applications for turbine engines in test rigs or working systems is not intended to be exhaustive but instead to give a sense of the breadth of the potential of MEMS in these systems.

Health (structural) monitoring

MEMS sensors would be used to monitor the health of engine casings, blades, and turbines, and the loads they are experiencing. These sensors could be linked to systems to adjust engine controls to avoid or reduce damage or as part of condition-based maintenance systems. For example, advanced composite structures need acoustic emission sensors with wireless connections to signal-processing and damage-monitoring nodes. Other sensors are needed for torque and thrust-load measurements, acoustic crack initiation detection,[4] and dynamic and high-temperature strain.

One such strain sensor might involve the use of a silicon cantilever excited to its resonant frequency. The strain acting on the sensor would be measured with a differential laser interferometer and would be determined by the maximal deflection and the geometry of the cantilever. This device could be exploited in the development of test and measurement equipment for new turbine engine systems.[5]

Other application areas include vibration sensing and control[6] and deicing using heaters embedded into engine structures that can be used to melt ice which can alter air intake flow and lead to compressor stall and engine failure.

Flow control and monitoring

MEMS-based systems can be used to meter the flow of fuel and air into combustors, control cooling air flow through engine sections, or control turbulent air flow or boundary layer separation to improve engine efficiency. The development of micro-atomizer components will provide more precise metering of fuel into the combustor section. Si micro-atomizers reproducibly create small droplets at lower pressures and precise spray angles over a wide range of fuel injection pressures. This control over droplet size and shape enhances mixing efficiency. Current MEMS development projects have produced working Si, SiC-coated, and SiC atomizers.[7] A number of issues still remain to be addressed, including the reduced erosion resistance of silicon atomizers over conventional atomizers and the extreme temperature requirements of the engine environment.

MEMS actuators can be integral parts of advanced cooling air and fuel flow and pressure control systems. One proposed MEMS system would reduce noise and high-cycle fatigue through controlled trailing edge blowing from upstream inlet guide vanes. This system would control pressure fluctuations and turbulence within the engine. A control system could be linked to MEMS-based microvalves and micropumps built into the vanes to regulate blowing air.[8]

Similar systems can be used to control leading edge air feed to pressure deficient blade tips as determined by pressure sensors. Increasing tip pressure at selected points can reduce leakage and improve turbine efficiency. Systems integrated with flow sensors can be used along with actuated flow splitters to control air bypass ratios, possibly along with embedded heaters to control cooling air temperatures, or act as stall detectors.

Actuators/Smart Structures

MEMS can be embedded in structural materials to create smart skins that can sense and adapt to changing environments. Smart skins could perform real-time monitoring and structural modifications of turbine components. In test rigs, they can be used to verify and improve finite-element-analysis models by providing microscale data.

One application of this type of technology would provide on-blade smart skin FOD (foreign object damage) detection.[9] Here, FOD or crack-initiation detectors would give pilots warning of potential imminent catastrophic failures and reduce pilot risk, as well as maintenance costs. Another application would be active clearance control for turbine blades, i.e., blades whose shape would change, depending on flow and temperature conditions, to minimize leakage.[10] Clearance control could also be effected through the use of synthetic microjets to control air flow.

Smart structures are currently being developed by DARPA as part of active inlet control systems in the SAMPSON program. The goal is to be able to modify turbine inlet shape so as to extend the performance envelope of next-generation fighter aircraft. These systems could include the use of MEMS sensors and actuators as part of the control mechanisms.

Sensors

Microsensors represent the most important application for MEMS in engines. Miniaturized sensing systems will enable finer control of engine function to optimize efficiency and reduce the size and cost of instrumentation. Utilizing MEMS-based instrumentation to validate fluid dynamics and materials performance models will help in this effort, by improving design capability and assisting integration and manufacturability. MEMS sensors can also fill the need in the engine development community for instrumentation that has longer life, greater reliability, lower cost, and is unobtrusive. In addition, MEMS can improve the accuracy of simulators through the introduction of sensors into hitherto inaccessible locations.

Miniaturized temperature sensors can be used to measure both air and surface temperature in engines. Air-temperature sensors would be used to monitor combustion process efficiency or hot gas ingestion into the engine. Surface measurements would enable temperature mapping of frames, blades, and combustor section walls. These—and in fact any MEMS sensors used in engines—would have to be nonintrusive so as not to interfere with engine air flow. Such sensors, for example, could be embedded directly into ceramic or metallic matrices and queried and powered remotely.

MEMS pressure sensors would be used to measure both steady-state and dynamic pressures. Steady-state pressure measurements can be used to monitor flow profiles, help adjust engine efficiency, or control stall and surge. Other sensors can monitor the flow of secondary and cooling air or pressures in the exhaust stream and feed the information back to control systems. Dynamic pressure applications include mapping pressure distributions on rotating parts (critical in controlling high-cycle fatigue) and monitoring the flow environment in the exhaust stream.

Vibration sensors could be embedded throughout the engine as part of a condition-based maintenance monitoring network, for example, to detect crack initiation and growth. Control of these vibrations is key in eliminating failures due to high-cycle fatigue. Nonintrusive, remotely queried accelerometers could monitor case vibrations as part of a control system that integrates sensors with piezoelectric actuators for vibration cancellation. Another key application would be the development of ice-detection systems based on resonant piezoelectric sensing elements and microprocessor control, for example.[11]

Gas emission sensors, including micro-spectrometers or SnO_2-based sensors, could be used to monitor engine emissions for environmental control or to sense key gas components to allow for active combustion control. These sensors could be a component on an integrated control system that monitors the efficiency and stability of the combustion process. Sensors would also monitor emissions for compliance with environmental standards. Specific goals include reducing NO_x emissions and using chemical information as part of condition-based maintenance systems. Integrated sensors could replace current expensive and time-consuming testing and analysis techniques, some of which involve using chase planes with scoops that collect exhaust samples from test engines in airplanes.

Strain sensing applications will also be an integral part of condition-based maintenance systems. Sensors which make dynamic strain measurements with microstrain accuracy are needed. These systems might be on flexible substrates for conformal application onto engine parts and preferably be networked using a telemetry system for data I/O. A key factor in the use of these systems will be the thermal stability and operating temperature ranges of any MEMS strain sensors.

Additional possibilities for applications of MEMS sensors to engine systems are nearly limitless. Force transducers could be used for measuring torque and thrust loading on parts.

Actuator/fuel valve position sensors would enable precision metering of fuel injection to enhance engine efficiency (and therefore reduce costs), as well as improve engine response to pilot actions.[12] Other sensors could be used to measure blade tip clearances dynamically, measure oil degradation chemically, or monitor engine noise.

Data transfer

MEMS-based telemetry provides the key to enabling nonintrusive devices that would link pressure, temperature, strain, or other sensors to full authority digital electronic control (FADEC) instrumentation for real-time monitoring of engine performance and condition. Wireless technologies would eliminate the need for extensive cabling during engine tests and be particularly useful when dealing with rotating parts. Advanced telemetry systems would also reduce time and cost of assembly and disassembly of test rigs. To realize the networked active structure systems envisioned for future engines, wireless transmitters and receivers built into MEMS sensors and actuator packages are critical. An example of such a system would be a thermo-microelectronic radio frequency (RF) transmitter.[13] This device would be powered by excess heat generated by the turbine engine itself. The transmitters would send RF signals short distance (< ~3 ft) from rotors to the engine casings at frequencies above engine background noise.

Technical Barriers

Currently, the hazardous environment limits the use of MEMS in turbine engines. Typical conditions that MEMS will experience in high performance aircraft engines include the following:[14]

- an operating temperature range between –40 and 3000+ °F and associated thermal shocks
- supersonic velocities
- case vibrations exceeding 100 g and at frequencies up to 20 kHz
- sound levels at 120 dB/Hz at frequencies out to 10 kHz
- dust and sand environment

New materials, device architectures, and packaging systems must be developed for MEMS to be feasible in turbine engines.

High-Temperature Survivability

At the high operating temperatures in the hot sections of a turbine engine, it is clear that silicon-based MEMS and the supporting silicon microelectronics will not survive. MEMS will fail due to excessive oxidation, mechanical failure, or electronic breakdown at elevated temperatures. Considerable effort is being made to improve the performance of silicon microelectronics at high temperature—simple silicon transistor operation has been demonstrated up to 462 °C[15]—however, it is not likely that silicon will ever be able to meet the temperature requirements of many engine applications.

SiC-based electronic devices and MEMS are currently being developed for use in high-temperature, high-power, and/or high-radiation conditions. SiC's high breakdown field, wide band gap, high carrier saturation velocity, and high thermal conductivity give it better operating performance at elevated temperatures than silicon. SiC exhibits a dielectric strength of 10 times that of Si and a thermal conductivity of 5 times that of Si. The standard overall Temperature Figure-of-Merit for SiC is 3 to 4 times that of Si.[16] SiC is relatively chemically inert, making it ideal for use in valves, pumps, or flow sensors operating in corrosive media. SiC's superior mechanical properties make these devices promising for operation in the presence of high loading, temperatures, and pressures as well as foreign object impact and violent chemical reactions. Some basic SiC MEMS, including atomizers and lateral resonators, have been grown and demonstrated. These devices have already shown significant reliability advantages in harsh environments over traditional polysilicon MEMS.

SiC device development is still in its infancy relative to silicon systems. In some ways, the material's chemical inertness makes it more difficult to process than Si. Much progress continues to be made in developing substrates, defect-free materials, and dopant systems for complex device architectures. Other research is focusing on developing other materials systems for high-temperature environments, including diamond and silicon-on-insulator (SOI) systems.[17] This work, as well as parallel research into high-temperature packaging and interconnects, is critical in laying the foundation for the use of MEMS in engine environments.

Structural Reliability

The structural reliability of MEMS also comes into question when considering turbine engine applications. MEMS must be at least as reliable as the components they are replacing to justify insertion into engine systems. Case vibrations and loading, which can cause failure in the metallic components of existing engines, may cause performance degradation in any embedded or surface-mounted MEMS. Surface components must be able to survive impacts of dust and sand particles that may be larger than the devices themselves. Any MEMS must also be able to survive high-temperature processing of engine materials. Here again, SiC's mechanical properties make it promising for use in engine applications.

Packaging

MEMS packaging must be developed to survive the high temperatures and vibrations in the engine environment. This packaging must also be designed to include required telemetry and power systems that will support the MEMS sensors and actuators. Innovative packaging techniques will be a prime factor in allowing MEMS achieve the form, fit, and function requirements of engine subsystems.

Packaging cost must also be reduced before affordable MEMS-based systems are produced. Currently, package costs are over five times the cost of the sensor alone. Often, any cost advantage gained by MEMS producers leveraging semiconductor manufacturing infrastructure is lost to expensive, application-specific packaging requirements. This problem must be resolved before MEMS can move from the laboratory to the commercial sector

Power

Another major technical barrier will be powering the MEMS inserted into the engine environment. Extensive networks of sensors and actuators in relatively inaccessible spaces must have on-board power sufficient for long term operation without maintenance. It is possible that this power can be supplied using RF transponder technology[18] or by generating energy using the heat or vibrations of the engine itself. Power packages must meet the overall goal of being nonintrusive within the engine.

System Integration

System integration issues will also determine how successfully MEMS will be inserted into turbine environments. MEMS developers will have to work closely with subcomponent manufacturers not only to meet technical performance requirements, but also power, communications, and data protocols. As part of this process, engine system and subsystem developers will need more information on the allowable operating environments and reliability of MEMS-based systems. More information on mean time between failure (MTBF) and failure mechanisms needs to be cataloged to enable substitution of MEMS for existing components.

Cost

The cost of MEMS-based systems must also become competitive with traditional engine instrumentation before any significant progress towards insertion can be made. This cost reflects the entire life cycle of the products, from research and development investments, to manufacturing, testing and evaluation; retrofitting costs; and maintenance and support. Government support of initial R&D programs and development of flexible manufacturing infrastructure for MEMS will serve to assist in making the technology an affordable commercial alternative.

Transitioning MEMS to Turbines

Past successes in the transition of technology from the laboratory to the field suggest some general principles which may apply to current efforts to accelerate adoption of MEMS technology within the gas turbine engine community. It is important to understand that past successes by no means guarantee future success; however, the specific circumstances surrounding the successful transition of technology in the past must be understood to draw the most appropriate lessons for MEMS technology transition.

Cautionary notes notwithstanding, there are certain "lessons from history" documented by the Federal Laboratory Consortium, the General Accounting Office, and a recently produced history of DARPA that are instructive.[19]

The first lesson to be learned is that technology transition from laboratory to field requires the establishment of an effective collaboration among the research and development (R&D) community, the user community, and the industrial base that will produce the fruits of R&D in meaningful quantities. Effective collaboration requires a common vocabulary, an appreciation for the similar and different imperatives that drive institutions, and products that are appropriate to the needs or requirements of the consumer. In the past, DoD focused on the supremacy of combat performance. Today, however, DoD must make conscious tradeoffs between combat performance on the one hand and the total cost of ownership on the other. Recent decisions by the Secretary of Defense reported in the Defense Reform Initiative (November 1997)[20] and subsequent Defense Reform Initiative Decisions (DRIDs) elevate the importance of total cost of ownership by making system cost an independent variable in the weapons acquisition process.

To reduce total ownership costs, the government is prepared to enter into a much wider variety of partnerships with the industrial base. The goal of acquisition reform is to move away from low bid to best value procurements. This will result in the lowest total cost of ownership over complete system life cycles. Initial acquisition costs must be balanced against reliability, maintainability, usability, sustainability, and personnel requirements (numbers, skill level, etc.). MEMS technology will transition far more quickly from laboratory to the field if engine developers take full advantage of expanded acquisition vehicles that promote collaboration throughout the development of the next family of systems.

The second lesson learned is that technology transition occurs best in balanced programs. The MEMS R&D community is engaged in the development of a broad range of technologies addressing high-temperature materials, packaging materials, sensors, recording devices, and data transmission. The broad technology development efforts within the MEMS community are intended to ensure that there exists a balanced set of opportunities and solutions that can be applied to the full range of technical needs within the gas turbine engine development process.

The third lesson is that system developers must engage developers of subsystems and of test and evaluation technology, as well as end users, in a continuous dialog that refines generic needs and requirements to very specific, focused problems and solutions based on cause and effect relationships. Good engineering solutions truly do depend on good science. But good science also depends on a clear understanding of the engineering challenges to be solved and the gaps in our understanding of fundamental principles. The need to take full advantage of advances in information processing and communication technology to disseminate problems and solutions as widely as possible has never been greater.

We have also learned that successful technology transitions from laboratory to the field have occurred when the participants in the transition process paid due care to the broader environment in which their efforts took place. The development and implementation of realistic technology roadmaps was essential to the transition of technologies ranging from semiconductor devices to the submarine launched ballistic missile (technologies in which DARPA played a key role).

Realism in this context refers to a dispassionate understanding not only of the process of scientific discovery and its reduction to engineering practice, but forthright and frank assessment of resource requirements and availability to ensure successful transition. All of the factors that affect success need to be carefully assessed, including those that are often neglected by scientists and engineers. The impact of politics (macro, micro, and nanoscale), rules and regulations (commercial, environmental, institutional, and human behavioral), as well as the pace of scientific discovery and engineering practice fuel the success of technology transition. Excessive projections of success create false optimism and keen disappointment, which in turn create greater barriers to transition in the future. The promised level of performance that is never quite attained results in dismissal of pleas for more resources; more time; and additional opportunities for research, development, and testing.

Technology roadmaps for MEMS technology transition require much better understanding of the precise location and path of MEMS development in absolute and relative terms. The MEMS R&D community must develop far better understanding of the range of MEMS and non-MEMS solutions to problems confronting the developers of new turbine engines. By working in consort with the engine development community, MEMS developers and producers can focus on those areas of technology where MEMS will have a comparative advantage and convey that advantage to the engine developers and operators. Engine developers also have an obligation to suspend their disbelief of MEMS devices and technology and define technical challenges in terms that present a fair, realistic, and reasoned set of challenges to MEMS and alternative technologies so that the best technology can be developed and deployed in the future.

As part of the test of realism, MEMS developers, as well as the engine development community, must sharpen their focus on those environmental factors that inhibit the development and transition of new gas turbine engine technology. Paths of least political, economic, technical, and budgetary resistance must be identified and followed. Rigorous use of the scientific method—reliance on past experimental success and the careful development and testing of new theories—offers exceptional opportunities to accelerate transition of MEMS technology from the laboratory to the field. But MEMS developers need to do their part by mining the literature of the field and contributing to its further growth and development. The extraction and contribution of new knowledge to the Defense Technical Information Center's archive is no longer a luxury—it is an absolute requirement both of contract and of science. Similarly, exploitation of existing government technology transfer opportunities through the use of Cooperative Research and Development Agreements (CRADAs), other Cooperative Agreements, partnering, and exploitation of new contractual vehicles should accelerate the dissemination and incorporation of MEMS technology by engine developers, where such technology is appropriate.

Another facet of realism is the recognition on the part of MEMS developers, as well as the engine community, that the resources provided by the government with which they are expected to perform are likely to shrink in real terms over the foreseeable future. Available dollars to support developmental testing will remain flat or decline. The number and diversity of test facilities and environments will remain constant or shrink. The requirement for accurate, precise, and complete collection of data during experiments has never been greater and is likely to grow as the use of constructive simulations in conjunction with laboratory testing expands. The need to develop new test and evaluation techniques for MEMS devices and new instruments incorporating MEMS devices, as well as using MEMS to support test and evaluation of gas turbine engines, must be fulfilled in an environment constrained by budgets, facilities, people, and time.

Finally, we have learned that technology moves from laboratory to field when researchers produce what in the world of software is termed "the killer app"—the one application everyone wants to have to be successful. While there are many possible uses for MEMS devices in the design, development, test, manufacture, and operation of future gas turbine engines, no one has identified the one application of MEMS technology that if successful would radically alter the path of engine development. Find a MEMS application that reduces the longest "poles" in the development process "tent" to little more than tent "pegs" and MEMS technology transition from the laboratory to the field will follow in short order. Making MEMS instrumentation technology worthwhile for insertion by the engine development community into the R&D process, the test and evaluation process, and ultimately the certification and licensing process will happen quickly if a small number of widely used devices with large economic or performance impact can be developed and deployed first within the R&D community. These types of successes will help to clear most barriers to insertion of MEMS into turbine engines and other systems.

The insertion of MEMS into engine systems shows promise for great economic and performance rewards. MEMS technology can be used innovatively to solve a number of key problems currently facing in the engine development community. Although there are significant technical and nontechnical barriers to the transition process, communication and cooperation between academia, industry, and government can ensure the quickest and most cost-effective path to MEMS technology insertion.

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[1] A. Pisano, Defense Advanced Research Projects Agency/Electronics Technology Office, "MEMS 2003," presented at DARPATECH '97, Kansas City, MO, 1997.

[2] USAF Scientific Advisory Board, *New World Vistas: Air and Space Power for the 21st Century —Aircraft & Propulsion Volume*, R.G. Bradley, 1995.

[3] "The Market for Turbofan, Turbojet and Ducted-Fan Aviation Engines, 1997–2006" in *Gas Turbine Forecast*, Forecast International, October 1997.

[4] L. Schmidt, private communication.

[5] T. Viel, GE Aircraft Engines, "Large Engines & PIWG," presented at the NAWCAD/IDA Workshop on Potential Applications of MEMS to Gas Turbine Engines, held at the Institute for Defense Analyses, Alexandria, VA, March 19–20, 1997.

[6] T. Viel, GE Aircraft Engines, "Large Engines & PIWG," presented at the NAWCAD/IDA Workshop on Potential Applications of MEMS to Gas Turbine Engines, held at the Institute for Defense Analyses, Alexandria, VA, March 19–20, 1997.

[7] M. Mehregany, Case Western Reserve University, "Microelectromechanical Systems," presented at the NAWCAD/IDA Workshop on Potential Applications of MEMS to Gas Turbine Engines, held at the Institute for Defense Analyses, Alexandria, VA, March 19–20, 1997.

[8] W. Ng, et al., Virginia Technical University, "MEMS-based Remote Sensing and Actuation in Jet Engines: Issues and Opportunities," presented at the NAWCAD/IDA Workshop on Potential Applications of MEMS to Gas Turbine Engines, held at the Institute for Defense Analyses, Alexandria, VA, March 19–20, 1997.

[9] L. Schmidt, private communication.

[10] L. Burwell, AlliedSignal Aerospace, "Challenges in Applying MEMS to Gas Turbine Engines," presented at the NAWCAD/IDA Workshop on Potential Applications of MEMS to Gas Turbine Engines, held at the Institute for Defense Analyses, Alexandria, VA, March 19–20, 1997.

[11] S. Roy, et al., Case Western Reserve University, "Detection And Measurement Of Ice Thickness Using Microprocessor-Controlled Resonant Transducers," Proceedings of the Conf. Smart Struc. and MEMS, SPIE Symp. on Smart Struc. and Mat., San Diego, CA (Mar. 1998).

[12] R. Clark, Pratt & Whitney, "Potential Gas Turbine Engine Applications of MicroElectricalMechanical Systems," presented at the NAWCAD/IDA Workshop on Potential Applications of MEMS to Gas Turbine Engines, held at the Institute for Defense Analyses, Alexandria, VA, March 19–20, 1997.

[13] W. Ng, et al., Virginia Technical University, "MEMS-based Remote Sensing and Actuation in Jet Engines: Issues and Opportunities," presented at the NAWCAD/IDA Workshop on Potential Applications of MEMS to Gas Turbine Engines, held at the Institute for Defense Analyses, Alexandria, VA, March 19–20, 1997.

[14] R. Clark, Pratt & Whitney, "Potential Gas Turbine Engine Applications of MicroElectricalMechanical Systems," presented at the NAWCAD/IDA Workshop on Potential Applications of MEMS to Gas Turbine Engines, held at the Institute for Defense Analyses, Alexandria, VA, March 19–20, 1997.

[15] M. Migitaka, Toyota Technological Institute, presented at the IEEE Conference on High-Temperature Materials, Devices and Sensors, San Diego, CA, February 22–27, 1998.

[16] M.N. Yoder, "Wide Bandgap Semiconductor Materials and Devices," *IEEE Trans. on Electron Devices*, Vol. 43, No. 10, 1996, p. 1633.

[17] N. Maluf, Lucas NovaSensor, "MEMS Technologies for Extreme Environments," presented at the Ohio Aerospace Institute Propulsion Instrumentation Working Group Micro Device Applications Workshop, Cocoa Beach, FL, January 28–29, 1998.

[18] M. Miller, Phase IV Engineering, "Applications of Transponder Technology to MEMS Sensors," presented at the NAWCAD/IDA Workshop on Potential Applications of MEMS to Gas Turbine Engines, held at the Institute for Defense Analyses, Alexandria, VA, March 19–20, 1997.

[19] Institute for Defense Analyses, *DARPA Technical Accomplishments: An Historical Review of Selected DARPA Projects. Volume 1,* IDA Paper P-2192, VOL 1, S.J. Deitchman, et al., 1989.

[20] Department of Defense, *Defense Reform Initiative Report*, W.S. Cohen, November 1997.

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Agenda

- Institute for Defense Analyses & DARPA/IDA MEMS Insertion Task
- Turbine Engines
- MEMS Applications in Turbine Engines
  - Structural Health Monitoring and Control
  - Active Flow Control
  - Environmental Sensing
  - Telemetry
  - Power Supplies
- Barriers to Insertion
- Technology Transition Issues

Institute for Defense Analyses

- Mission
  - Assist the Office of the Secretary of Defense, the Joint Staff, the Unified Commands, and Defense Agencies in addressing important national security issues...requiring scientific and technical expertise
- Operates two Federally Funded Research and Development Centers (FFRDC)
- Core competencies
  - Systems Evaluations
  - Technology Assessments
  - Resource and Support Analyses
  - Force and Strategy Assessments
  - High Performance Computing and Communications

DARPA/ETO MEMS Program

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MEMS Program Manager
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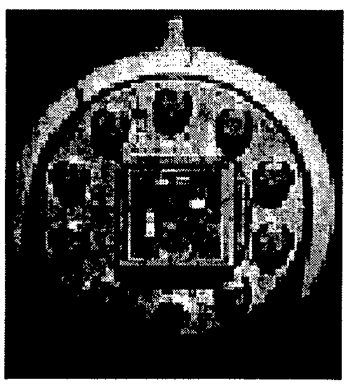

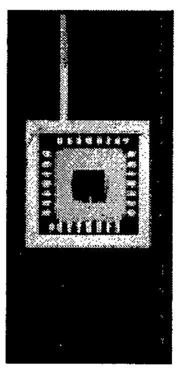

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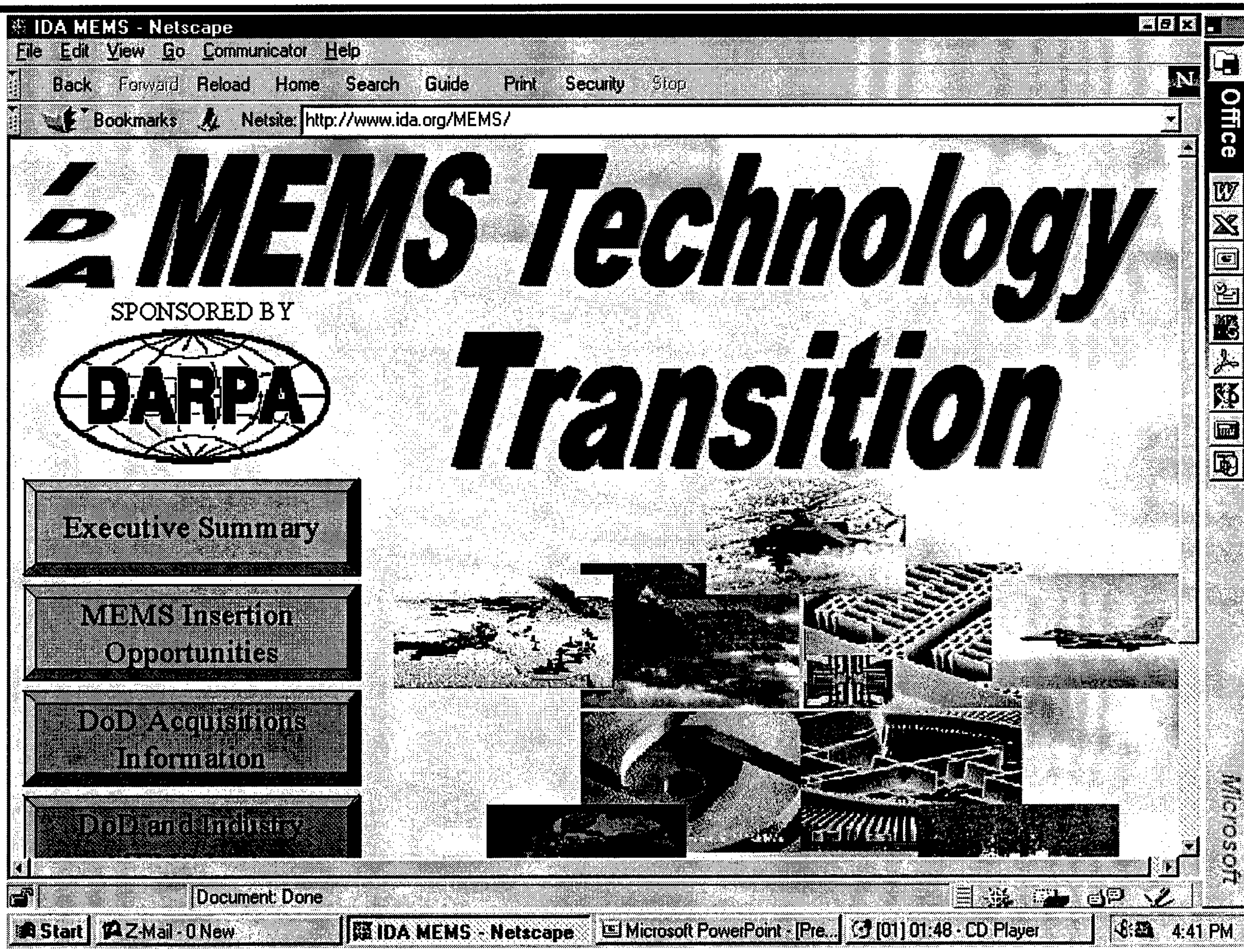
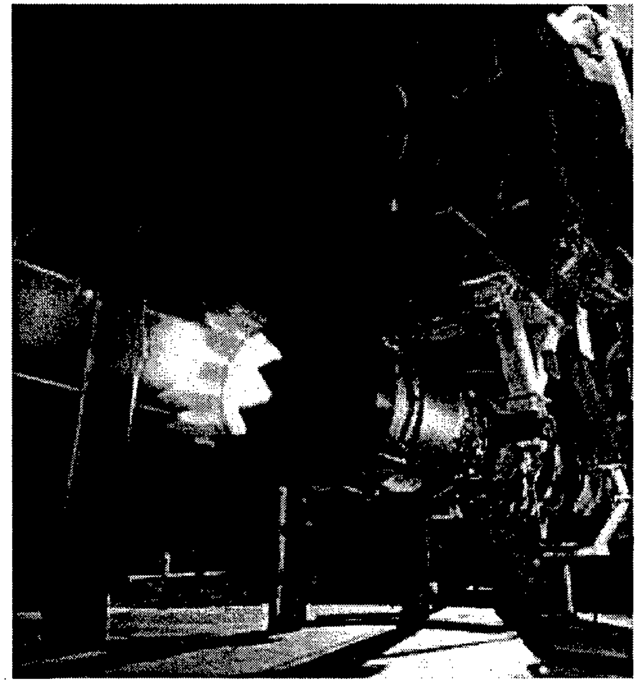


Turbine Engines Are Important

DoD Applications

- Jet Engines
- Rotary Wing Vehicles
- Cruise Missiles
- Stationary Power Supplies for fixed installations or marine systems
- Armored Vehicles
- UAVs

~50,000 Fielded Systems



Potential DoD Customers of MEMS for Turbine Engines

- Air Force Research Laboratory Propulsion Directorate
- DoD Integrated High Performance Turbine Engine Technology (IHPTET) Program
- Propulsion Instrumentation Working Group (PIWG)

Turbine Engines are Important

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- Huge Commercial Market (1997-2006)
  - Turbofan and Turbo-jet Aeroengines: $136.6 Billion
  - Turboprops: $7.9 Billion
  - Industrial and Marine Gas Turbines: $96.6 Billion
  - Aviation Turboshafts: $8.2 Billion
  - Small Engines and APUs: $6.0 Billion
  - TOTAL: $255.3 Billion
- Interest of Engine Manufacturers in Improving Technology

SOURCE: Forecast International, 1997

Advantages of MEMS

IDA

- Low Batch Fabrication Costs
- Size, Weight, Power Reduction
- Integrated Sensing, Processing, Actuation, and Control
- Enables Active Sensing and Control Systems
- Enables Conditioned-Based Maintenance
- Potential Performance Advantages
- Potential Reliability Advantages

Potential Applications in Engines

- Test and Development
- Flow Physics and Modeling
- Operational

- Structural Health Monitoring and Control
- Active Flow Control
- Environmental Sensing
- Telemetry
- Sensor/Actuator Power Supplies

NAWCAD/IDA Workshop on Potential Applications of MEMS to Gas Turbine Engines - *March 1997*

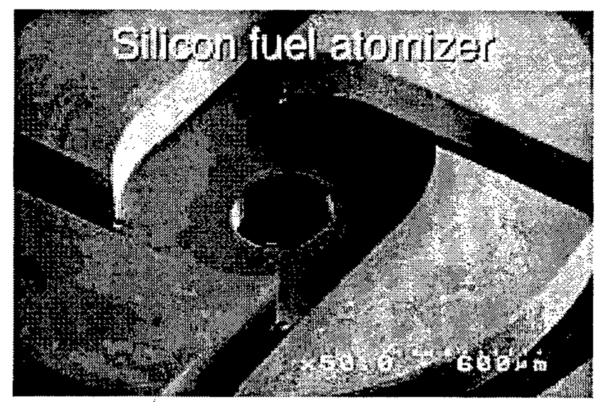
Structural Monitoring & Control

- Systems needed to sense
  - strain
  - blade clearance
  - vibration
  - torque and thrust loads
  - foreign object damage (FOD)
- Systems needed to control
  - engine noise/vibration
  - inlet shape for enhanced efficiency
  - icing
  - strength of structures on demand

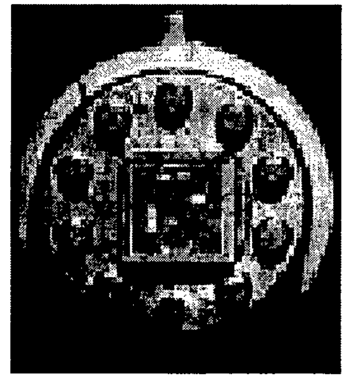
Active Flow Control

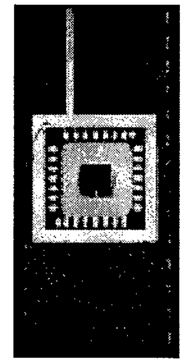
IDA

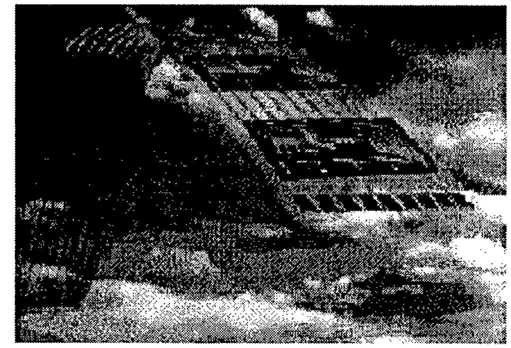
- Systems to monitor and control air flow through engine
  - boundary layer control
  - blade tip clearance control
  - shock wave limitation
- Fuel-air mixture control to maximize combustion efficiency
- Cooling air flow control for enhanced engine performance



Sensing in Engine Environment







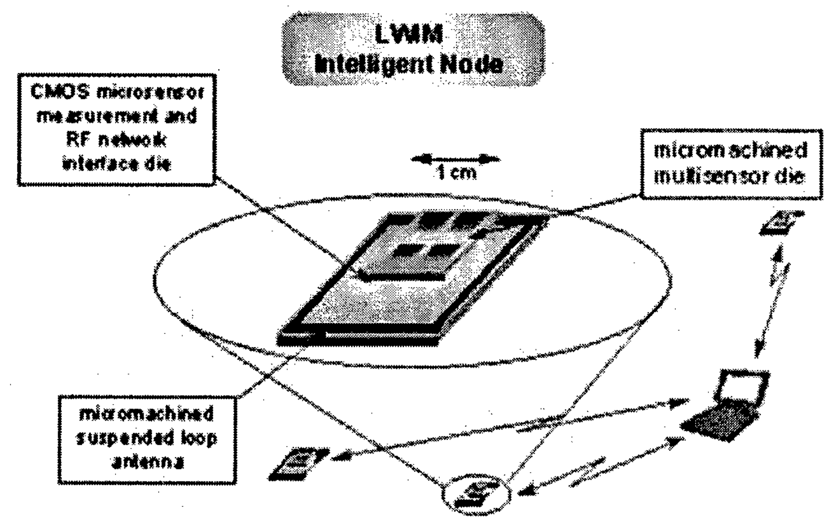
- Flow
- Vibration
- Temperature
- Strain
- Pressure Sensors for Stall/Surge Control
- Fuel Valve Position Sensors
- Chemical Sensors for Emissions Monitoring

KEY: Integration of sensing, processing, communications, control and actuation

Telemetry

- Wireless links between sensors, recorders, and control systems
  - communication to embedded sensors
  - integrated structural monitoring systems
  - communication to air flow control actuation systems
  - blade stress monitoring linked to FADEC

- Embedded transponder technology



Subsystem Power

- Power for microsensors and actuators
- Approaches
  - Microturbines
  - Miniaturized fuel cells
  - Thin film batteries
  - Thermo-microelectronics powered by engine heat or vibrations

Engine Environment

MEMS Needed to Operate in Harsh Environments

- Operating Temperature: -40 to 3000+ ^{o}F
- Dust and Sand Environment
- Supersonic Velocities
  - » Mach 2+ for fighters
- Mass Flow > 250 PPS
- Case Vibrations exceed 100g and out to 20 kHz
- Acoustic sound level at 120 dB/Hz out to 10KHz

Packaging Issues

- Environmental Requirements
  - Temperature
  - Vibrations
  - Loads
- Form/Fit/Function in System
  - integrated within engine system as a whole
  - embedded systems
- Cost
  - For sensors: sometimes 5x cost of device
  - unique package requirements are too expensive

Materials Issues

- Silicon
  - fabrication and cost advantage
  - reliability in hazardous environments
- Silicon Carbide
  - higher temperature devices
  - chemically inert
  - superior mechanical properties
  - some fabrication progress
- Other Materials Systems
  - diamond, SOI
- Packaging & Interconnect Materials

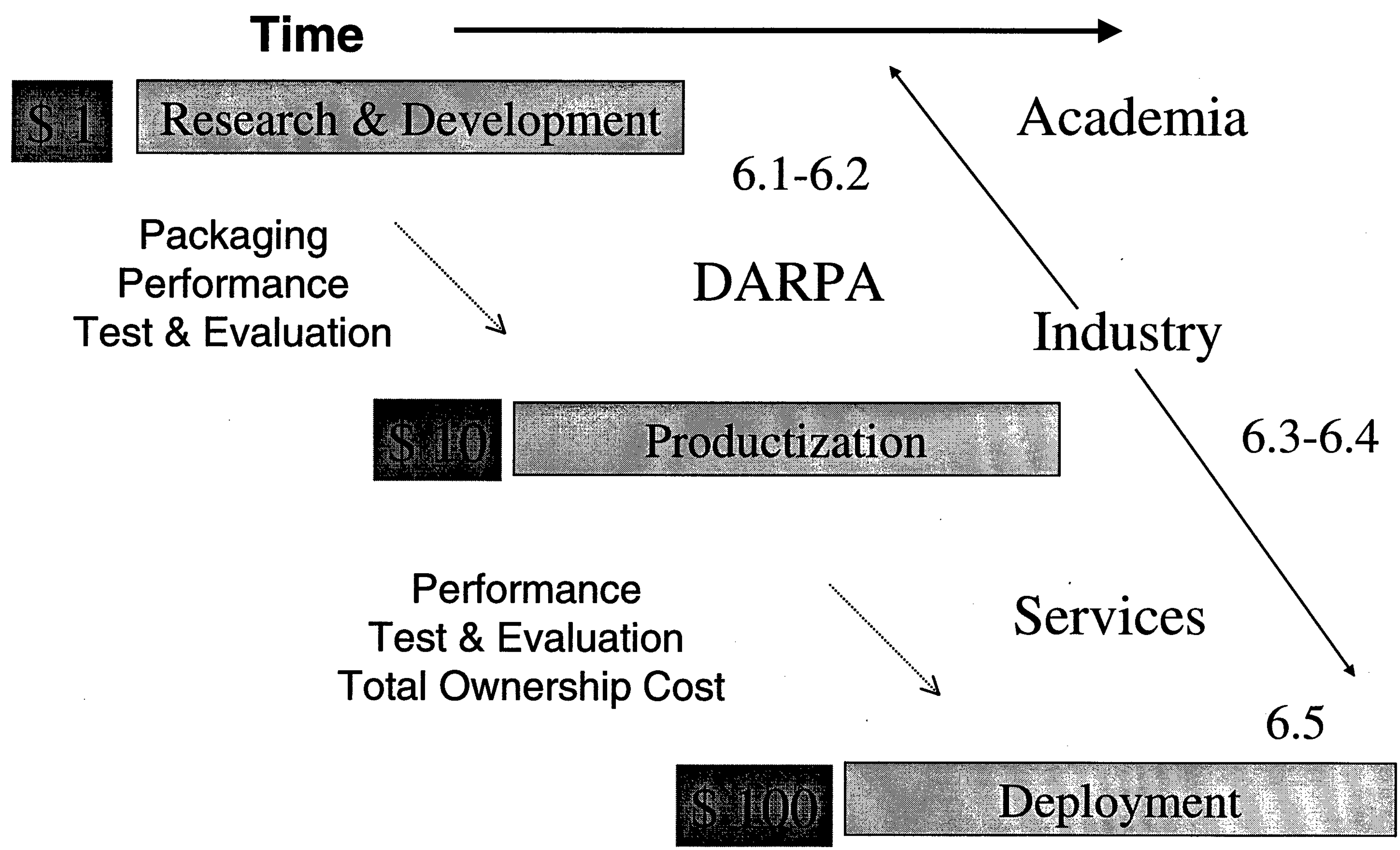
Cost & Reliability

- MEMS must be contribute to reducing total ownership costs
  - Research & Development
  - Manufacturing
  - Testing and Evaluation
  - Retrofit Costs
  - Maintenance and Support
- MEMS must be as reliable as every other part in system
  - Need data on failure mechanisms and MTBF
  - Modeling of MEMS in systems

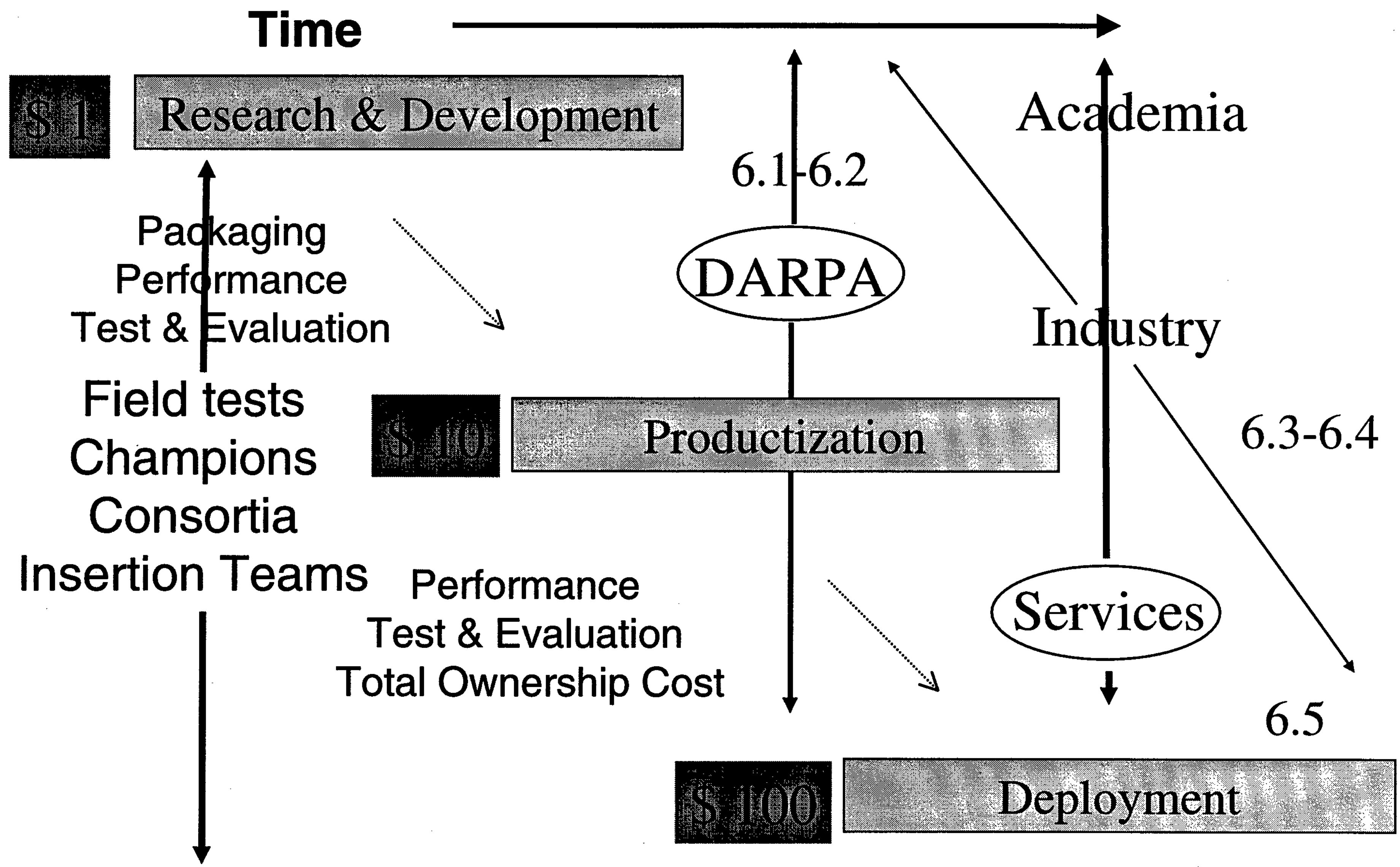
Successful Technology Transition

- Collaboration Between Funders, Developers, Integrators, and Users
- Balance of Technology Development
- Communication of Issues
- Realistic Technology Roadmaps
- Killer Applications

Technology Transition



Technology Transition (New)



Collaboration

- Understanding of different goals of major players
  - Government funding agencies
  - MEMS technology developers
  - R&D Entrepreneurs
  - System integrators
  - Warfighters
- Partnerships and consortia development to reduce technology development costs

Balance

- R&D progress in a broad range of technologies
  - materials
  - packaging
  - MEMS sensors and actuators
  - test and evaluation
  - data transmission

- Technology development in a variety of places
  - universities
  - government
  - industry (large and small)

Communication

- Engage technology developers, integrators, testers, and users in a dialog
- Specify technical requirements for sensors and actuator performance to feed to MEMS developers
- Represent accurately the current state of technology to integrators, testers, and users
- Build consensus on nature and location of barriers to insertion

Realism

- Achievable technology roadmaps
- Accurate representations of technical payoffs and timelines for technical advances
- Follow paths of least bureaucratic resistance
  - tie into existing programs
  - exploit government technology transfer
- Rational use of shrinking resources

Killer Applications

- Find “tickle points” where MEMS insertion gives biggest payoff
- Prove success in R&D applications in order to sell to industry and government
- Find champions
- Killer can mean cheaper or greener

Conclusions

IDA

- MEMS enables many capabilities to lower cost and improve engine performance
  - novel sensing, actuation, and control
  - telemetry

- Significant technical and non-technical barriers to successful insertion exist
  - MEMS performance in engine applications
  - resources for RDT&E and commercialization

- Technology transition strategies are almost as important as the technology itself

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There are many promising insertion opportunities for micro-electromechanical systems (MEMS) in turbine engines. Applications for novel control systems include sensors, actuators, and communications systems in networks. Significant technical barriers, including hazardous environments, packaging, and power, may limit the utility of MEMS in engines. Innovative technology transition strategies that rationalize both technical and nontechnical barriers to technology insertion must be developed to bring about MEMS usage by the engine development community.

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